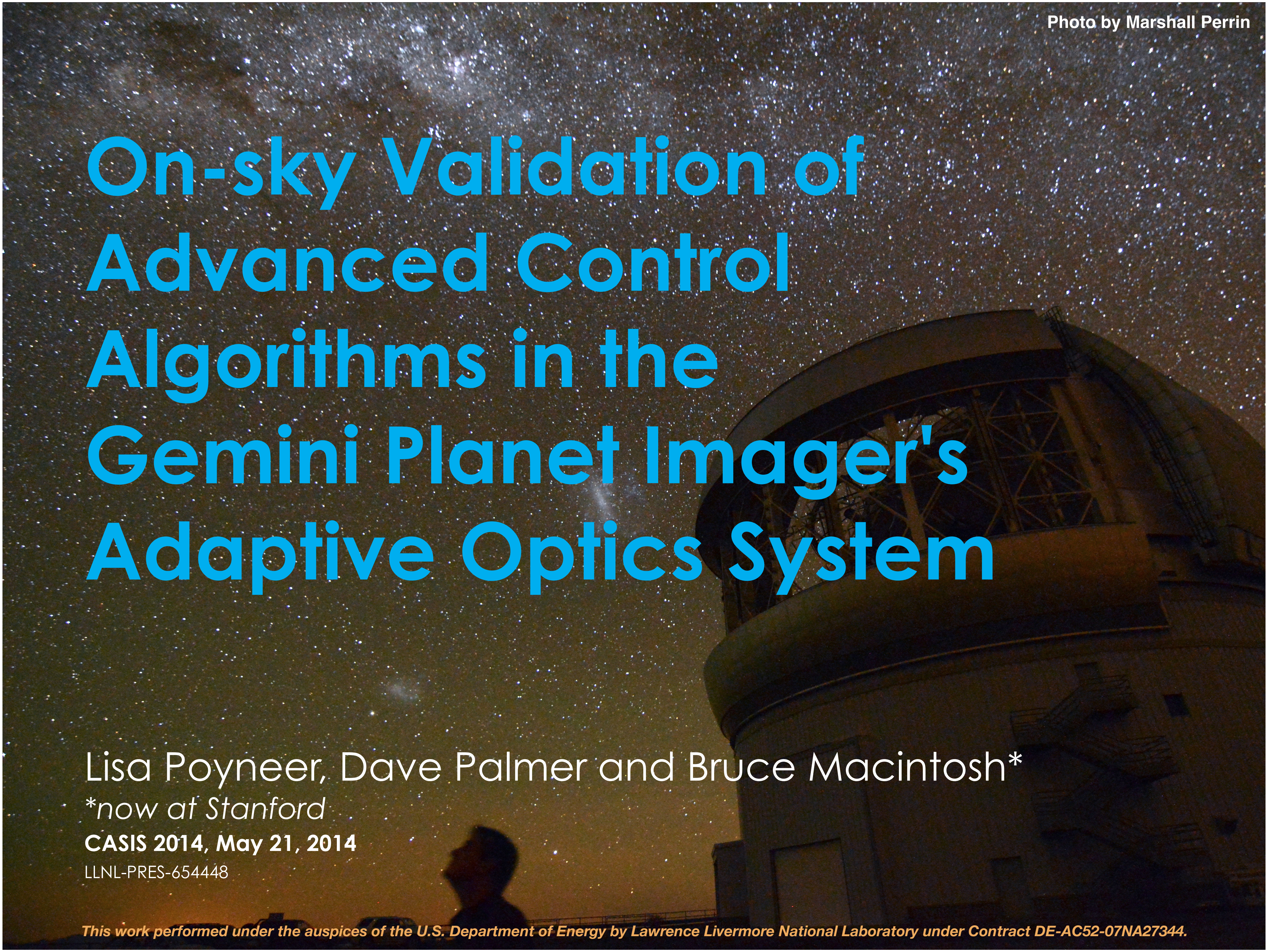


Photo by Marshall Perrin

On-sky Validation of Advanced Control Algorithms in the Gemini Planet Imager's Adaptive Optics System

Lisa Poyneer, Dave Palmer and Bruce Macintosh*
*now at Stanford

CASIS 2014, May 21, 2014

LLNL-PRES-654448

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Challenging vibrations in GPI

- IFS CCRs shake the instrument
- Internally, this causes vibration in pointing (Tip/ Tilt) at 60 Hz and harmonics
- Externally, this shakes the primary mirror of the telescope a very small amount, which causes a large phase error at 60 Hz

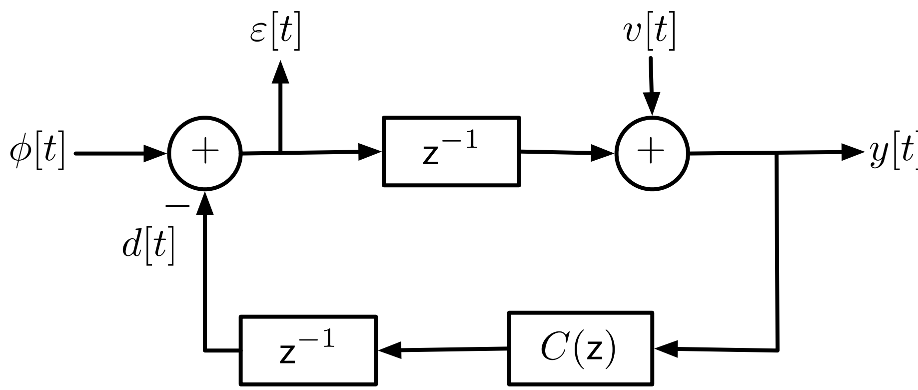
- 60 Hz is near the system bandwidth; 120 and 180 are in the overshoot

Kalman filter/LQG

- Linear-quadratic-Gaussian (LQG) control:
  - ***Linear system under additive Gaussian noise***
  - ***Quadratic cost function***
  - ***Results in an Estimator and a Regulator***
- Kalman filter
  - ***Is the Estimator for LQG***
  - ***Statistically optimal estimate of system state given all previous knowledge***
- If we apply the appropriate linear function of the Kalman state as the correction, we have an LQG controller

State-space model

- State vector contains
  - ***Underlying aberration***
  - ***AO measurements and commands***
- Matrices describe
  - ***A: aberration evolution***
  - ***B: driving noise***
  - ***C: measurement process***
  - ***D: DM commands via vector u[t]***



$$\mathbf{x}[t] = (\mathbf{a}[t], \phi[t-1])^T$$

$$\mathbf{x}[t+1] = \mathbf{A}\mathbf{x}[t] + \mathbf{B}\mathbf{w}[t]$$

$$y[t] = \mathbf{C}\mathbf{x}[t] + \mathbf{D}\mathbf{u}[t] + v[t]$$

Vibration: 2nd order model

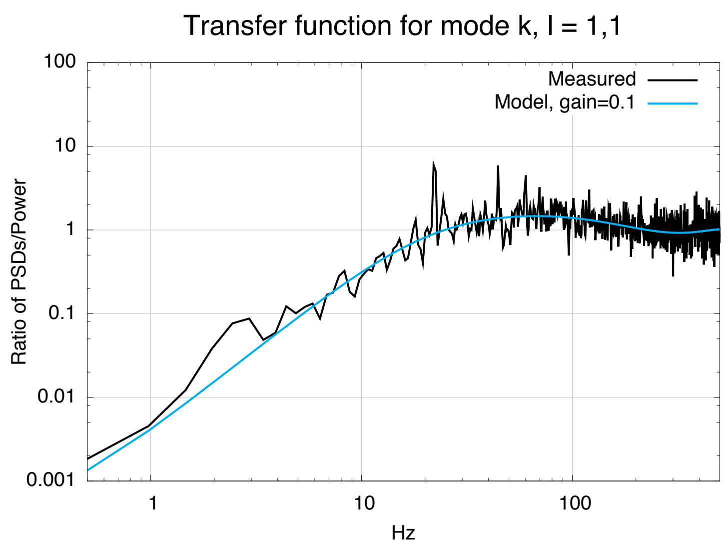
- We implement the vibration as:

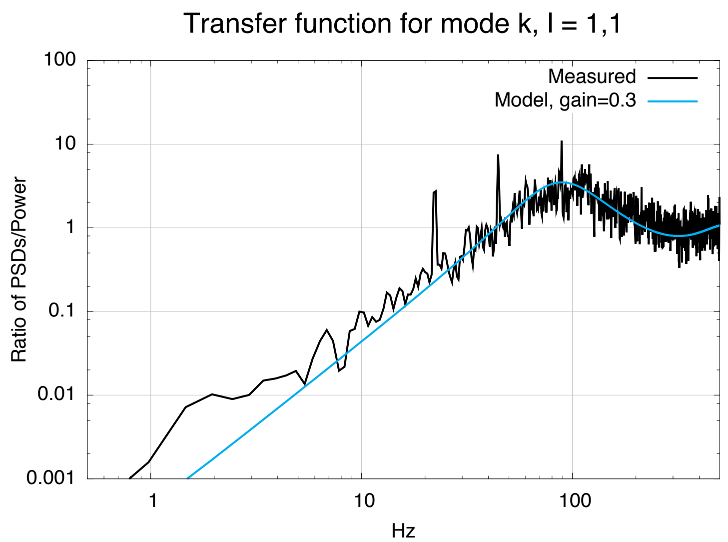
$$\begin{pmatrix} a_r[t+1] \\ a_i[t+1] \end{pmatrix} = \begin{pmatrix} \alpha_r & -\alpha_i \\ \alpha_i & \alpha_r \end{pmatrix} \begin{pmatrix} a_r[t] \\ a_i[t] \end{pmatrix} + \begin{pmatrix} w_r[t] \\ w_i[t] \end{pmatrix}.$$

- Alpha is complex
  - ***magnitude (< 1) controls depth of notch***
  - ***phase sets temporal frequency of vibration***
  - ***power of driving noise controls depth and width of notch***

System model is accurate

- Record measurement signal ‘y’ both ‘open-loop’ and ‘closed-loop’
  - ***can do on either just WFS noise, or on a ‘phase plate’***
- Estimate temporal PSDs of measurements
- Ratio of closed to open PSDs is the same as the error transfer function

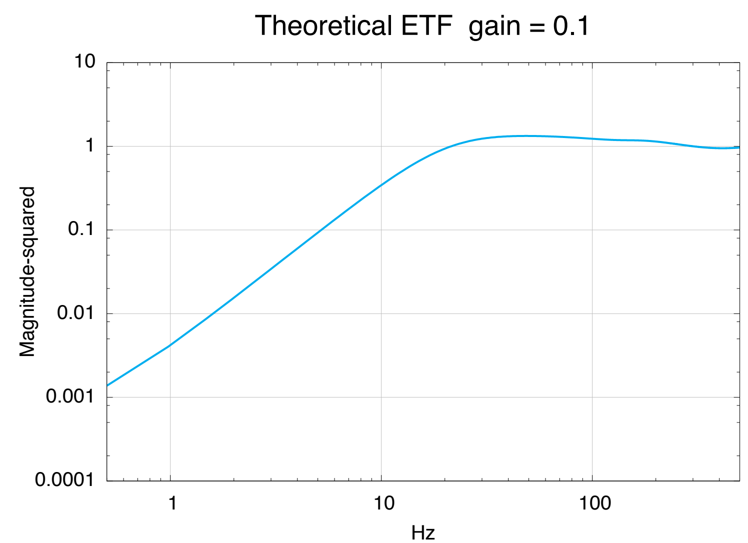


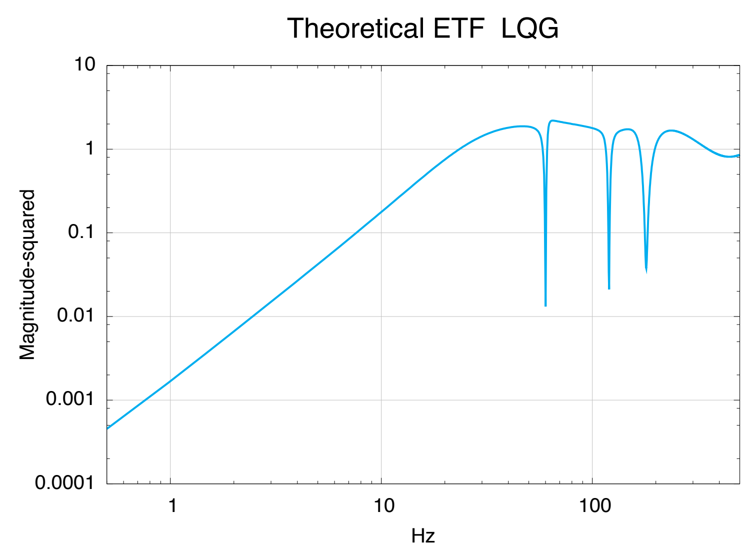


Data sets _When_2013.12.9_17.37.53, _When_2013.12.9_17.43.31 taken on calibration source

Pointing LQG: filters

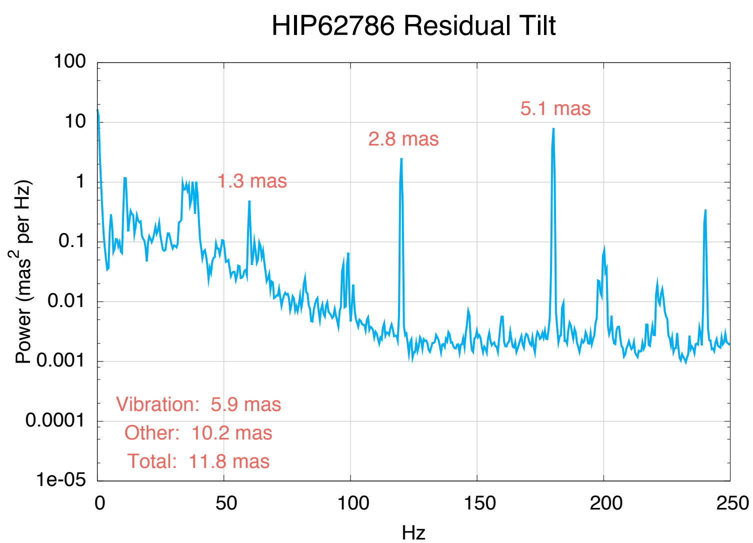
- Tip and Tilt are pulled out of centroids before reconstruction
- Corrected with LQG and split temporally between TT stage and DM
- Designed the filter to correct 60, 120 and 180 Hz with moderate notches

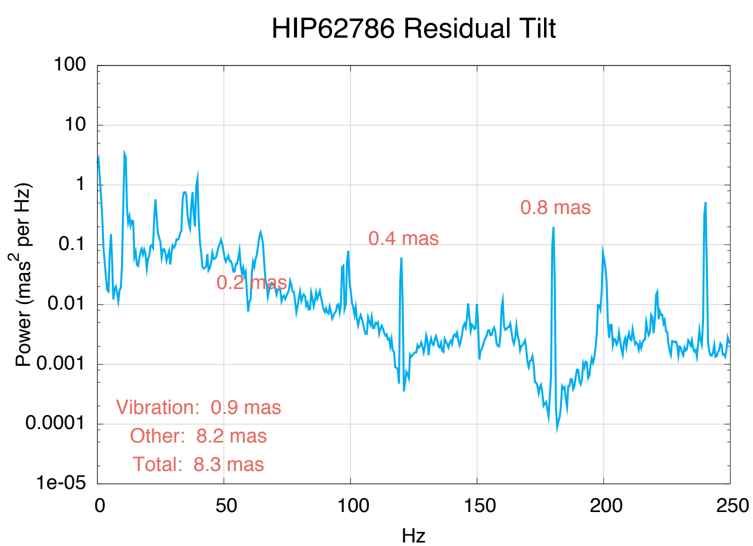




Pointing: on-sky improvement

- Vibration reduced from 6 to 1 mas
- Atmospheric rejection maintained
- Higher overshoot is fine for this noise level

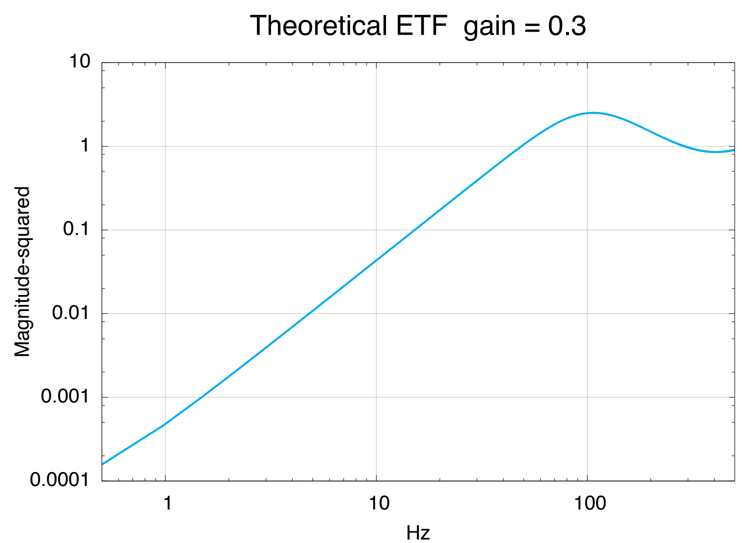


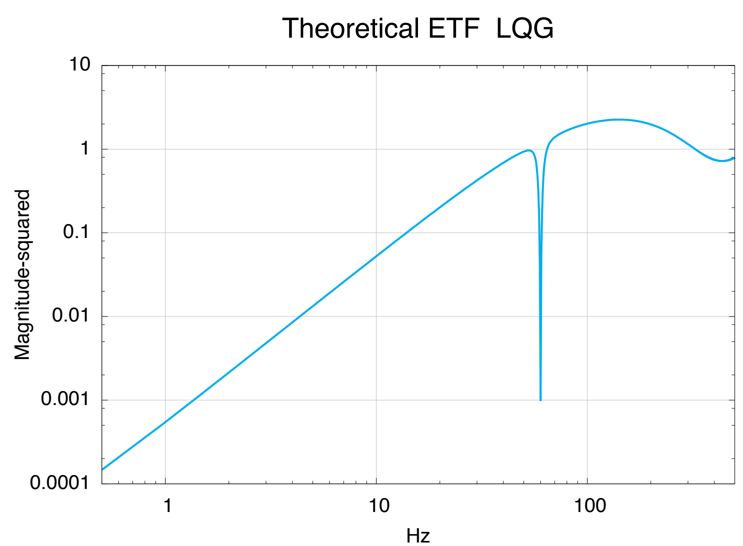


Data sets _When_2014.5.12_19.50.22 and _When_2014.5.12_20.14.6

Focus LQG: filters

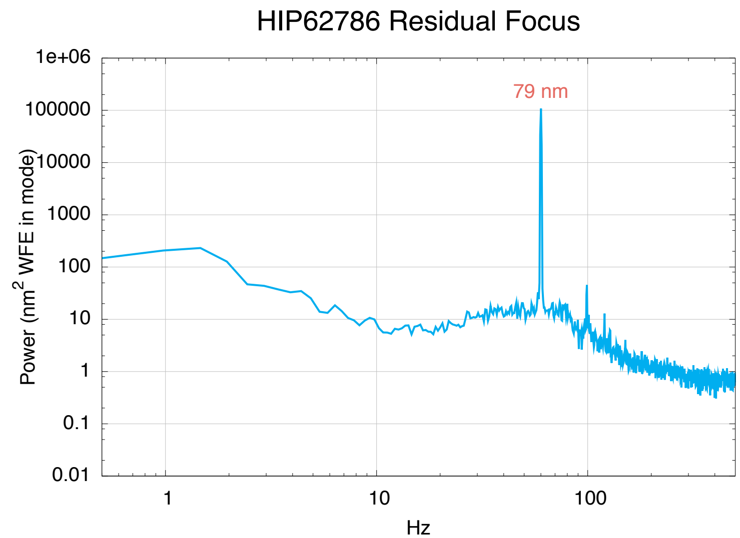
- Focus shape is pulled out of centroids before reconstruction
- Corrected with LQG and sent directly to DM
- Designed the filter to correct 60 Hz with a very deep and narrow notch

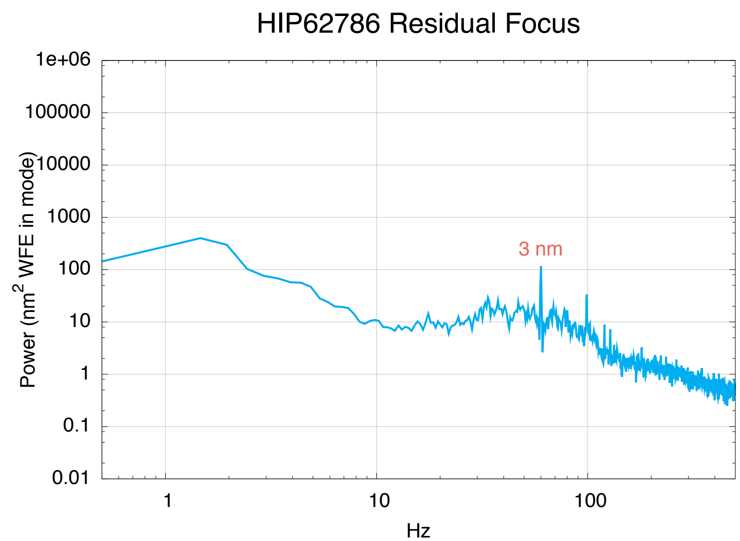




Focus: on-sky improvement

- Vibration strongly rejected: reduced from 79 to 3 nm
- Atmospheric rejection maintained
- Slightly higher overshoot is insignificant for this noise level





Data sets _When_2014.5.12_19.50.22 and _When_2014.5.12_20.14.6

Conclusions

- GPI needs to correct for specific high-frequency vibrations
- We use the LQG (Kalman) framework for advanced control
- These vibrations are selectively fixed with negligible impact on overall correction
- On-sky results for vibration reduction:
  - ***Pointing: 6 to 1 mas***
  - ***Focus: 79 to 3 nm***